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A RE-AUTOFRETTAGE PROCEDURE FOR MITIGATION OF BAUSCHINGER EFFECT IN THICK CYLINDERS

Anthony P. Parker

**Royal Military College of Science
Cranfield University, Swindon, SN6 8LA, England**

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Anthony P. Parker

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Royal Military College of Science
Cranfield University, Swindon, SN6 8LA, England

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ABSTRACT

A manufacturing procedure for enhancing residual stresses and thereby improving fatigue lifetime and fracture resistance of pressure vessels is proposed. The procedure involves initial autofrettage; one or more 'heat soak plus autofrettage' sequences and an optional final heat soak. Stresses are calculated numerically for traditional, single autofrettage and compared with those created by the new procedure. The loss of bore compressive hoop stress due to Bauschinger effect is shown to be significantly reduced. Associated fatigue lifetime calculations indicate that life may be improved by a factor of between 2 and 30, depending upon tube geometry and the ratio of cyclic pressure to yield strength. Repeated overload plus heat soak cycles may also be of benefit in other engineering design scenarios.

INTRODUCTION

Prior to normal use many engineering components and structures are subjected to overloads in excess of their design operating level. Examples of such overloads are autofrettage of a pressure vessel (including gun barrels) and mandrel enlargement of fastener holes (including aircraft structures).

In general the purpose of such overloads is to cause the stresses within the material(s) to behave in an inelastic fashion at design-critical locations and thereby, on removal of initial overload, to induce advantageous residual stresses at or near the critical locations. These residual stresses subsequently serve to mitigate the stresses due to normal operation and thereby improve fatigue lifetime and/or improve fracture resistance and/or inhibit re-yielding. For example, in the case of a typical pressure vessel, the use of autofrettage can increase the fatigue lifetime of a tube with pre-existing crack-like defects by approximately one order of magnitude [1].

Many materials exhibit the Bauschinger effect [2] that serves to reduce the yield strength in compression as a result of prior tensile plastic. The principal features of a uniaxial test of a pressure vessel steel are illustrated in Figure 1.
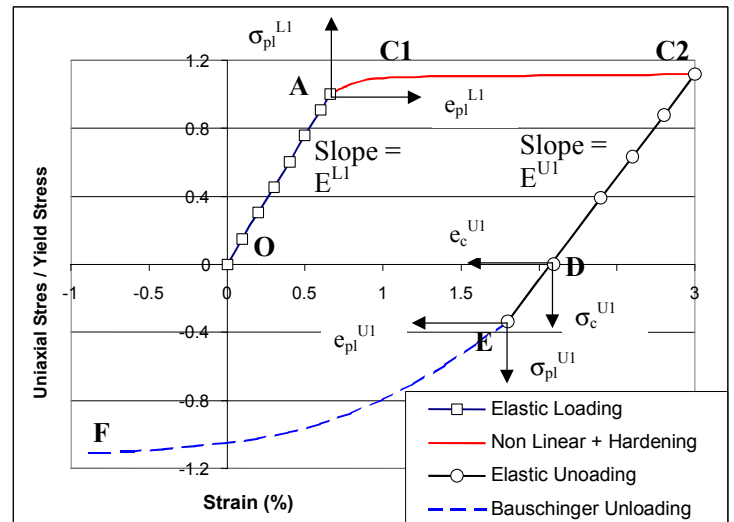
Figure 1: Schematic Uniaxial Stress – Strain Behavior Showing Strain Hardening, Reduced Elastic Modulus in Compression and Bauschinger Effect.

Loading: An initial tensile loading regime, O-A, during which the steel behaves elastically up to the yield point σ_Y defined by a given percentage offset. The elastic modulus over this range is E^{L1}. The material then behaves plastically, A-C1-C2. This phase may involve significant non-linearity, A-C1, and predominantly linear strain hardening (or softening), C1-C2. In the case of A723 steel regime A-C2 is characterized by modest linear strain hardening over a strain range of e_{pl}^{L1}.

<u>Reversed Loading</u>: Reversal of loading with elastic modulus E^{U1}. The tensile (positive) stress reduces and subsequently becomes compressive (negative). At some point after load reversal behavior becomes non-linear moving asymptotically towards a bound. The value of stress at point E, the onset of non-linearity, is $-\beta\sigma_Y$ where β is the Bauschinger effect factor [3]. Both β and the shape of the curve E-F are a strong function of the maximum initial plastic strain e_{pl}^{L1*}.

It is often assumed that the Bauschinger effect is associated with the pile-up of microscopic dislocations at grain boundaries and the associated creation of microscopic zones of residual stress [4]. The reduction of yield strength after load reversal is of importance because, on removal of the overload, critical regions experience high values of reversed stress. This may approach the magnitude of the yield strength if the unloading is totally elastic. If, because of Bauschinger effect, the combination of stresses exceeds some yield criterion non-linear behavior will occur thus losing much of the potential benefit of overloading. A less significant cause of reduced residual stress is the reduction in elastic modulus, i.e. E^{U1} is less than E^{L1}; again the relationship between E^{U1} and E^{L1} may be expressed as a function of initial plastic strain [3].

The loss of residual compressive hoop stress due to Bauschinger effect has been quantified for the case of Von Mises' criterion applied to open-end tubes [1]. Such tubes are overloaded during an autofrettage process involving extremely high bore pressures or displacements. The proportion of the wall thickness which behaves plastically during autofrettage is termed the 'overstrain'. As a rule of thumb, for typical diameter ratios and overstrain levels, 'ideal' residual compressive hoop stress at the bore is reduced by 30% by Bauschinger effect and associated effects. For example, the fatigue lifetime of a typical tubular steel pressure vessel subjected to 80% overstrain which does not exhibit Bauschinger effect may be more than one order of magnitude greater than the same pressure vessel which does exhibit Bauschinger effect. Hence, if it were possible to eliminate the deleterious impact of the Bauschinger effect the lifetime of the component would be very significantly increased.

There has been examination of a 'double autofrettage' procedure wherein the tube is autofrettaged once and then, without any intervening process, is subjected to a second similar autofrettage cycle. Apart from a modest contribution due to further strain hardening and/or 'ratcheting' of the material, such a process produces little or no benefit in compressive residual stress [5].

In some procedures, such as the post-autofrettage treatment of gun tubes, it has been common practice, following overload, to 'heat soak' all or part of the structure by way of a slowly applied heating and cooling process in order to stabilise the material. Typically for an A723 type gun steel the heat soak is undertaken at around 675F for a period of 6 hours. It has been opined that heat soak produces a 'healing' effect at the microscopic level such that dislocation pile-ups caused by the overload are very significantly dissipated or removed.

A popular experimental method for assessing the residual stresses within an autofrettaged tube is Sachs' method as described by Weiss [6]. In its usual form this involves fixing axial and hoop direction strain gauges to the OD of a tube; strain readings are then obtained after each incremental removal of material from the bore. Sachs' analysis assumes that the remaining tube unloads in linear-elastic fashion throughout the process and that superposition may therefore be employed to quantify the residual stresses within the original tube. Unfortunately the assumption of elastic unloading is invalidated by the Bauschinger effect [7]. However, in order to overcome this limitation a modified Sachs' procedure has been proposed by Kendall [8]. This involves heat-soaking the specimen prior to material removal so that subsequent behavior is predominantly elastic and the Sachs' procedure is valid [8]. There is also evidence from the testing of both uniaxially-strained steel samples, and sections cut from autofrettaged gun tubes, that plastically overstrained material behaves in a predominantly elastic fashion after heat-soaking [9].

PROCEDURE AND STRESS ANALYSIS

The observations in [6-9] imply that there may be benefit in further autofrettage cycle(s) following the initial autofrettage plus heat-soak sequence. The procedure proposed herein differs from autofrettage plus heat soak and from autofrettage plus autofrettage and involves: Initial autofrettage; one or more (heat soak + autofrettage) sequences and an optional final heat soak.

The heat soak causes microscopic dislocations to be reduced or eliminated whilst retaining macroscopic residual stresses due to the previous overload. Assuming that the material then responds effectively as virgin material containing a pre-existing residual stress field when the next overload is applied, plastic strain, and hence Bauschinger effect, during second and later autofrettage is thereby dramatically reduced. This behavior is analogous to autofrettage of pre-shrunk tubes wherein there has been no prior plastic deformation [10].

Specific examples will now be described by way of an example with reference to the accompanying Figures 2-5. Values of stresses and strains presented within Figures 2-5 are based upon a standard numerical stress analysis procedure [1] which was extended to permit the incorporation of pre-existing residual stress fields from prior loading sequences, as described in [10].
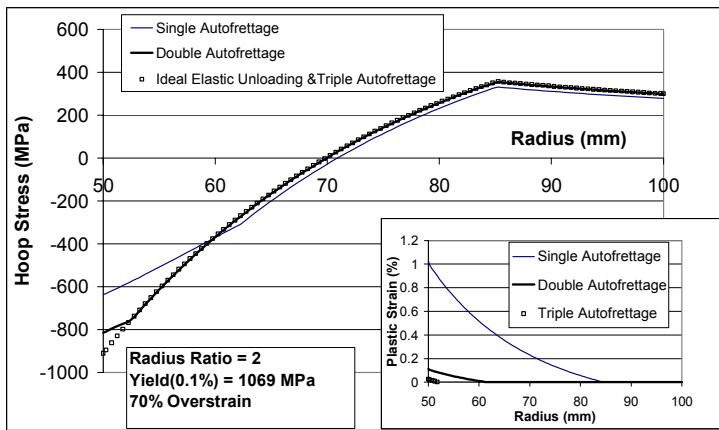

Figure 2: Residual Hoop Stresses and Percentage Plastic Strain for Single, Double and Triple Autofrettage. A723 Steel, 0.1% Yield Strength 1069 MPa, 70% Initial Overstrain, Radius Ratio 2.0.

Figure 2 shows residual hoop stresses in a tube of radius ratio 2 after 70% overstrain. The tube is modelled as being made of a typical (A723 type) pressure vessel steel having 0.1% offset yield strength of 1069 MPa. The curve marked 'Ideal Elastic Unloading' indicates the residual stresses that could be achieved in the absence of Bauschinger effect. The curve 'Single Autofrettage' shows the residual stresses actually achieved after single autofrettage of the tube with Bauschinger effect present. The curve 'Double Autofrettage'

indicates the residual stresses after initial autofrettage, heat soak to remove microstructural effects due to prior plastic strain whilst retaining macroscopic residual stresses, and second autofrettage with Bauschinger effect related only to plastic strains during second autofrettage. It indicates that much of the bore hoop compressive stress 'lost' to Bauschinger effect during single autofrettage may be recovered by such a process. If a further (triple) autofrettage is applied after a further heat soak the residual stresses are then coincident with the 'Ideal' profile. The inset plot showing maximum plastic strain during autofrettage indicates the apparent reason for such improvements; the maximum plastic strain at the bore has been reduced from 1.02% during initial autofrettage to 0.11% during second autofrettage following heat soak and further reduced to 0.03% during third autofrettage following heat soak. This reduction serves to dramatically reduce or eliminate Bauschinger effect.
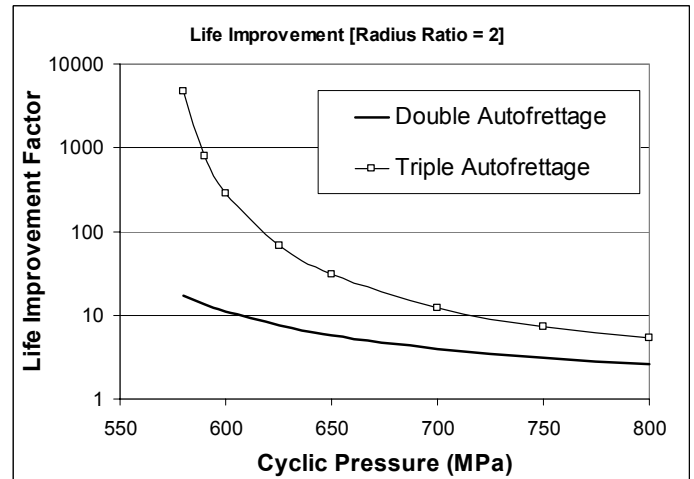

Figure 3: Life Improvement Factor for Double and Triple Autofrettage. A723 Steel, 0.1% Yield Strength 1069 MPa, 70% Initial Overstrain, Radius Ratio 2.0.

Calculations for a pressure vessel with pre-existing crack-like defects, based upon Paris' fatigue crack growth law [11] using material properties typical of an A723 steel [1], show that the fatigue lifetime of such a tube, loaded by cyclically applied internal pressure, would be increased as a result of such a procedure. The increase in fatigue lifetime for a range of cyclic pressures is shown in Figure 3. The plot shows life improvement ratio (i.e. lifetime after

3

multiple autofrettage plus associated heat soaks divided by lifetime after single autofrettage). Thus for example, when the cyclic pressure is 650 MPa, double autofrettage increases life by a factor of 5.7 and triple autofrettage by a factor of 30.2.
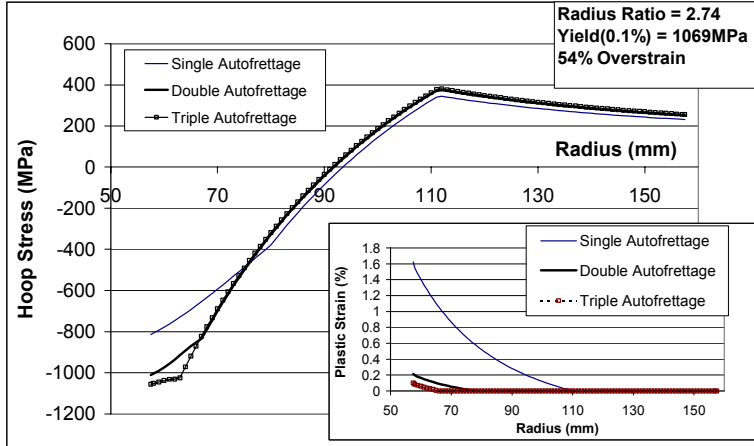

Figure 4: Residual Hoop Stresses and Associated Percentage Plastic Strain for Single, Double and Triple Autofrettage. A723 Steel, 0.1% Yield Strength 1069 MPa, 54% Initial Overstrain, Radius Ratio 2.74.
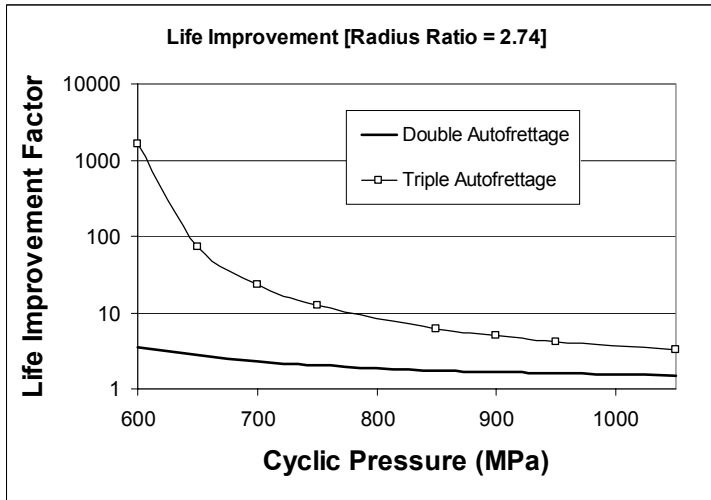

Figure 5: Life Improvement Factor for Double and Triple Autofrettage. A723 Steel, 0.1% Yield Strength 1069 MPa, 54% Initial Overstrain, Radius Ratio 2.74.

The benefits also extend to much thicker tubes, Figure 4 shows residual hoop stresses and plastic strains in a tube of radius ratio 2.74 subjected to 54% overstrain with single, double and triple autofrettage plus intervening heat soaks. The life improvement ratio for a range of cyclic pressures is shown in Figure 5. When cycling at 850 MPa, double autofrettage increases life by a factor of 1.8 and triple autofrettage by a factor of 6.2. In this case, because of increased wall thickness, the higher compressive stress extends to a greater depth. The latter effect will further benefit both fatigue and fracture behavior.

DISCUSSION AND CONCLUSIONS

Previous work involving re-autofrettage and heat-soak as separate operations indicates the possibility of a sequence that combines both operations. The procedure proposed herein involves initial autofrettage, one or more 'heat soak plus autofrettage' sequences and an optional final heat soak. Using numerical stress analysis this is shown to enhance residual stresses and is thereby predicted to improve fatigue lifetime and fracture resistance of pressure vessels. Stresses were calculated for traditional, single autofrettage and compared with those created by the new procedure. The loss of bore compressive hoop stress due to Bauschinger effect was shown to be significantly reduced. Associated fatigue lifetime calculations indicated that life may be improved by a factor of between 2 and 30, depending upon tube geometry and the ratio of cyclic pressure to yield strength. The concept proposed herein has not yet been tested experimentally; methods for verification include tube-slitting and measurement of opening angle, Sachs' method investigation, X-ray and neutron diffraction and hydraulic testing to measure fatigue lifetime.

Repeated overload plus heat soak cycles may also be of benefit in other engineering designs which incorporate overload or 'shakedown'.

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